SHEAR STRENGTHENING OF RC DEEP BEAMS WITH LARGE OPENINGS
USING CARBON FIBER REINFORCED POLYMERS (CFRP)

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ABSTRACT

This research deals with the experimental study of the behaviour of reinforced concrete deep beams with or without large rectangular openings as well as openings strengthened using externally bonded Carbon Fiber Reinforced Polymer (CFRP) composites in shear. The structural behaviour, including the load deflection, cracking patterns, failure mode, and effectiveness of the CFRP wraps were investigated. A total of four (4) specimens of beams with compressive strength of 35 MPa were tested to induce shear failure under 4 points loading test, which included one solid deep beam acted as a control beam (CB), one of which was tested without strengthening (US-BRO), and the remaining beams were strengthened with CFRP wraps in varying configurations around the opening (S-BRO-1, S-BRO-2). The beam had a cross section of 120 mm in width and 600 mm in depth as well as a length of 2400 mm. All the test specimens had a same geometry, main reinforcement arrangements and openings location. All the preparatory works of specimen materials were conducted in Laboratory FKASA. The examined parameter was the effect of configurations of the CFRP wraps used for the shear strengthening. The inclusion of un-strengthened large rectangular openings in the shear zone of a reinforced concrete deep beam leads to a reduction of ultimate beam strength by approximately 70%. The application of CFRP wraps with the presented strengthening configurations restricted the propagation of the diagonal crack and effectively increases ultimate load-carrying capacity as well as the ductility of the beam. The strength re-gains by U-shaped strengthening configuration around the openings was approximately 36% as compared to the beam with un-strengthened openings. However, the deep beam with U-shaped CFRP with horizontal fiber strengthened at the top and bottom chords of the openings were not capable to restore the control beam's original structural strength remarkably. The beam only managed to re-gain about 41% of the control beam's capacity.

ABSTRAK

Laporan kajian ini adalah mengenai kelakuan rasuk konkrit bertetulang yang mendalam dengan atau tanpa lubang segi empat tepat yang besar dalam ricih serta lubang diperkukuhkan dengan menggunakan terikat luaran Carbon Fiber Reinforced Polymer (CFRP) komposit. Kelakuan struktur mengandungi graf beban dan lenturan, corak retakan rasuk, mod kegagalan, serta keberkesanan balutan CFRP telah disiasat. Sebanyak empat (4) spesimen rasuk dengan kekuatan mampatan 35 MPa telah diuji untuk mendorong kegagalan ricih di bawah 4 titik ujian beban, termasuk satu rasuk dalam pepejal bertindak sebagai rasuk kawalan (CB), salah satu yang telah diuji tanpa pengukuhan (US-BRO), dan baki rasuk diperkuatkan dengan CFRP balutan dalam pelbagai konfigurasi sekelilingnya (S-BRO-1, S-BRO-2). Rasuk dengan ukuran keratan rentas 120 mm lebar dan 600 mm dalam dan panjang 2400 mm. Semua spesimen ujian mempunyai geometri yang sama, tetulang utama dan lubang lokasi. Semua kerja-kerja penyediaan bahan spesimen telah dijalankan di Makmal FKASA. Parameter diperiksa adalah kesan konfigurasi daripada balutan CFRP yang digunakan untuk pengukuhan ricih. Penggunaan lubang besar dalam bentuk segi empat tepat yang tanpa diperkukuhkan dalam zon ricih rasuk konkrit bertetulang yang mendalam telah menunjukkan pengurangan kekuatan rasuk sebanyak 70%. Penggunaan CFRP balutan dengan konfigurasi mengukuhkan dibentangkan dapat mengehadkan penyebaran retak pepenjuru dan berkesan meningkatkan keupayaan menanggung beban muktamad dan kemuluran rasuk. Kekuatan yang didapatkan semula dengan penggunaan CFRP terikat luaran balutan dalam konfigurasi berbentuk-U sekitar lubang adalah sebanyak 36% berbanding dengan rasuk mengandungi lubang yang tanpa diperkukuhkan. Walau bagaimanapun, rasuk dalam dengan CFRP berbentuk-U dengan gentian mendatar diperkukuhkan oleh CFRP terikat luaran balutan dalam konfigurasi-U berbentuk sekitar lubang di chords atas dan bawah lubang tidak mampu mengembalikan kekuatan asal kawalan rasuk struktur biasa. Rasuk hanya berjaya memerlukan memulihkan kekuatan rasuk sebanyak 41% daripada kapasiti rasuk kawalan itu.

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LIST OF SYMBOLS

%	Percentage
a/d	Shear span-to-depth ratio
d	Distance from the support (mm)
N/mm^2	Newton per millimetre square
l/h	Span-to-depth ratio
Kg	Kilogram
Kg/m^3	Kilogram per meter cube
N	Newton
℃	Degree Celsius
°	Degree
k	Kilo
g/m^2	Gram per meter square
mm^2	Millimetre square
Mm	Millimetre
µm	Micrometre
MPa	Mega Pascal

LIST OF ABBREVIATIONS

ACI	American concrete institute
AS	Australia standard
ASCE	American society civil engineer
BS	British Standard
C	Cube sample
CB	Control beam
CFRP	Carbon fiber reinforced polymer
CSA	Canadian standard association
EC	Egyptian Code
FRP	Fiber Reinforced Polymer
LVDT	Linear variable displacement transducer
MB	Mechanical expansion bolts anchoring system
S-BRO-1	Beam with u-shaped strengthened openings
S-BRO-2	Beam with surface strengthened openings
SG	Electrical resistance strain gauges
SGFRP	Sprayed glass fiber reinforced polymer
US-BRO	Beam with un-strengthened openings

CHAPTER 1

INTRODUCTION

1.1 BACKGROUND OF STUDY

The application of reinforced concrete (RC) deep beams is typically applied in high-rise building, foundation, and offshore gravity type structures. It can be seen normally at the lower floors or basement in multiple-story buildings, which used as transfer girders in order to avoid the columns and thus providing more free space for parking purposes. Reinforced concrete deep beams is very useful in supporting the high loading in a structure, the upper part load is transferred to others column through the transfer girders. Since the transfer girder is subjected high shear stress, thus the deeper depth is demanded. Due to their economic efficiency and convenience, this application has enhanced dramatically.

The fundamental requirement of constructing a modern building consists the networks of ducts and pipes so as to facilitate the necessary services such as electricity, telephone line, sewerage, computer network, ventilation system and so on. In the past practices, for the aesthetic viewpoints, these pipes and ducts were installed and hanged underneath the floors slab or beam soffits, then covered by the suspended ceiling where the dead space is formed. These dead space height in each floor gather up to the entire building height. Hence, the presence of the openings in web of RC beam is becoming an alternative solution and frequently used to accommodate those necessary services. In the meantime, it can be significantly eliminates overall height of the dead space, construction and material cost such as the length of the pipes and ducts, and results in more compact and economical design, but the saving is not much effective for smaller buildings (Ahmed et al., 2012; Hafiz et al., 2014; Mansur and Tan, 1999; Torunbalci, 2002).

There are several definitions regarding deep beam according to different country design codes. Generally, a reinforced concrete deep beam is defined as a structural member with large depths to span or has a span to depth ratio of less than 5. Instead, deep beam does not behave the same way like normal beam do, deep beams transmit the shear forces to support by way of compressive stresses rather than shear stresses. The flexural cracks and diagonal cracks are the cracks that typically germinate in RC deep beams (Farghaly & Benmokrane, 2013). Thus the typical assumptions cannot be taken for granted. As per New Zealand Code, deep beam is subjected to load on one face and supported on the opposite face thereby compression struts can be developed between the supports and loads as well as have either clear span equal to or less than 3.6 times the effective depth for continuous or simply supported beam, while clear span equal or less than 1.6 times the effective depth for cantilever beams.

According to American Concrete Institute (ACI 318R-08), the clear span of a deep beam are either equal to or less than 4 times of the overall depth. The EC 203-2006 has the same circumscription as ACI 318R-08, while the EuroCode defined deep beam as a member whose span is equal or less to 3 times the overall depth. ACI-ASCE Committee 426 also classifies a beam with shear span-to-depth ratio (a/d) less than 1.0 as deep beam and a beam with a/d exceeding 2.5 as an ordinary shallow beam. In addition, shear span is the defined as the zone where distance between a reaction and the nearest load point and shear force is constant. Other than that, as per IS-456 Clause 29, the ratio of the effective span of the overall depth of simply supported deep beam is less than 2 while the continuous beam is less than 2.5. The Canadian code (CSA-A23.3-2004) defined deep beam in the ratio of the clear span to the overall depth is less than the 1.25 and 2.5 for simply supported and continuous beam.

1.2 PROBLEM STATEMENT

Due to the architectural or mechanical requirement, the enlargement of the openings cannot be avoided and undoubtedly weakened the structural member's shear capacity significantly and then rendering severe safety hazard (El Maaddawy & Sherif, 2009). There have been numerous studies of experimental have been concluded that the increase in the height and depth of the opening lead to a significant reduction in the beam strength. The reduction in beam strength is more significant when the opening interrupted the load path (Mansur, 1998; Mansur *et al.*, 1999; Ashour and Rishi, 2000; El Maaddawy & El Ariss, 2012). In general, shear failure of concrete beams happened without advance warning prior to failure (Chin *et al.*, 2012).

The introduction of the large opening in reinforced concrete deep beam transformed the beam’s behaviours into a more complicated state due to the sudden change of beam cross section (Ahmed *et al.*, 2012; Torunbalci, 2002; Mansur *et al.*, 1992; Mansur, 2006). The previous practical and experimental studies have reported that the inclusion of a transverse opening in the web of the reinforced concrete deep beam produced discontinuities in the normal flow stresses, increase in deflection, and deduction in shear capacity and stiffness of the beam at load services stage. Other than that, introducing the transverse opening resulted the opening corners subjected by high stress concentration, thus cause the early unacceptable excessive cracking frequently (inclined and vertical cracks adopt at the corners of the opening) (Ahmed et al., 2012; Chin et al., 2012). Even though the collapse load was decreased, but it won't alter the mode of failure (Abdalla et al., 2003; Hawileh et al., 2012; Torunbalci, 2000).

1.3 RESEARCH OBJECTIVES

i. To determine the behaviour of deep beams with openings in terms of load-deflection and cracking patterns.
ii. To determine the behaviour of deep beams with openings strengthened using CFRP wraps strengthened in terms of load-deflection behaviour and cracking patterns.
iii. To determine the effects of opening shape, size and location.
iv. To determine the effective strengthening configuration using CFRP wraps.

1.4 SCOPE OF STUDY

This test was conducted on reinforced concrete deep beams included the large rectangular opening in the shear region in the experimental program of this research. The RC deep beams were designed as an under reinforced section in accordance with

American Concrete Institute (ACI 318R-08). The shear span-to-depth ratio (a/d) of the beams was 0.83 that's designed to actuate the shear failure and develop the deep beam action. A total of 4 reinforced concrete deep beams undergoes the 4 points loading tests which including one solid deep beam acted as a control beam, one deep beam with un-strengthened openings and remaining deep beams with strengthened opening using CFRP wraps with varying arrangements and configurations. All the reinforced concrete deep beams had the same geometry with a cross section of 120 mm in width and 600 mm in depth as well as a length of 2400 mm. The beams were simply supported at its ends, which placed 300 mm from the end of the beam. Thus had an effective span of 1800 mm which giving a l/h ratio (span-to-depth ratio) of 3. In addition, two concentrated point loads are positioned 500 mm away from the support point as well as at a distance of 800 mm apart were applied to the top of the beam.

All the beams were cast simultaneously in a horizontal direction by using the high strength ready mixed concrete with a nominal designed for 28-days compressive strength of 35 MPa. All the specimens had two openings, one in each middle of the shear span except the control beam. The openings shape and size were created and maintained constant throughout the test which is a rectangular shape with a cross section of 600 mm in depth and 270 mm in width. The internal web reinforcement was not allowed to erect in the test region. The crack patterns and load-deflection behaviour were also determined in this experimental study.

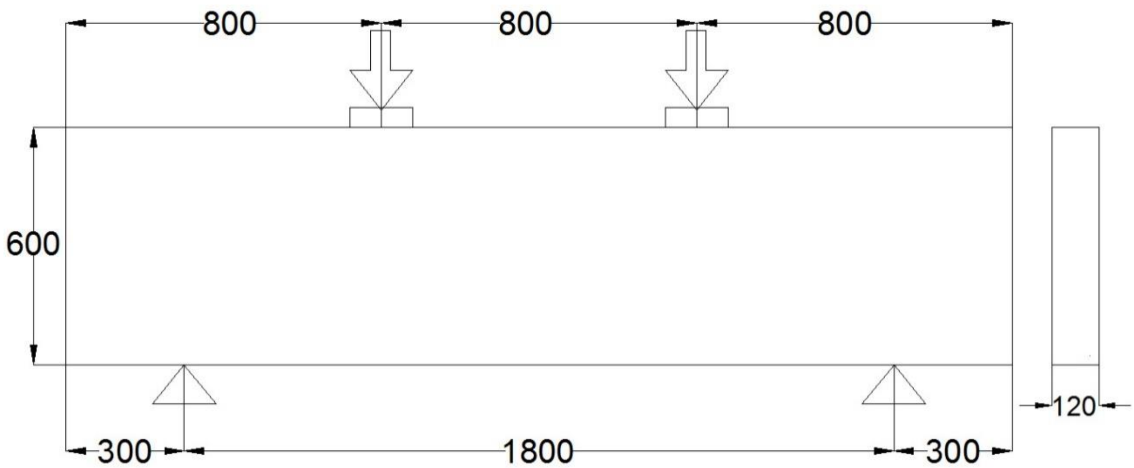

Figure 1.1: Illustration of solid deep beam (value in mm)

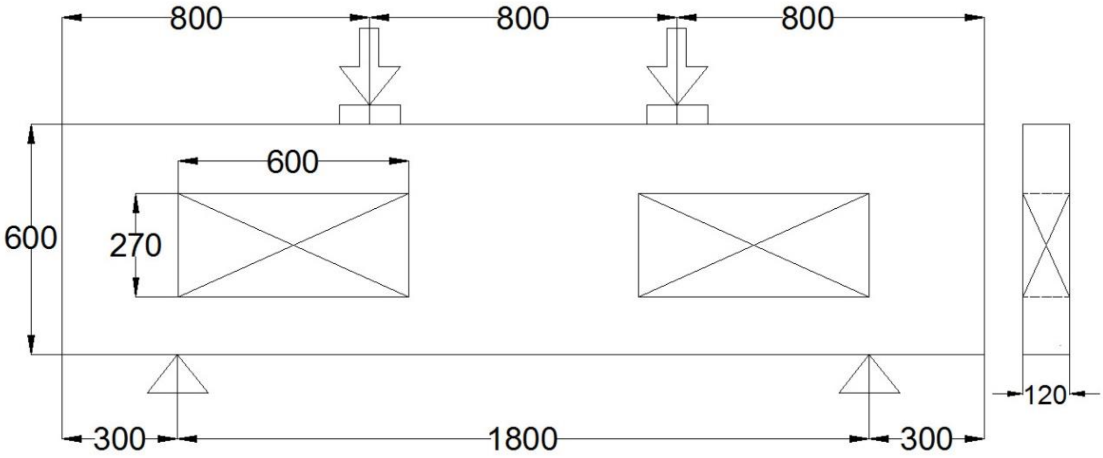

Figure 1.2: Illustration of deep beam with rectangular openings (value in mm)

1.5 RESEARCH SIGNIFICANCE

The present paper is intended to provide the experimental information about the load deflection behaviour, cracking pattern and ultimate load of RC deep beams with un-strengthened openings and strengthened openings using CFRP wraps in two different configurations. Hence, the important of this research contributed experimental result and evidences about the behaviour of RC deep beams with large rectangular opening.

The present research also intended to examine the potential use of this technique as a structural engineering solution to upgrade the RC deep beams with enlarged openings. The most effective CFRP configuration in enhancing the beam ultimate strength of RC deep beams with openings was also examined. Other than that, its purpose is to contribute the experimental evidences that would aid practicing engineers and researchers to better understand the interrelationship between the opening location, size, ultimate strength, load-deflection behaviour and failure mode of the RC deep beam with un-strengthened opening as well as the re-gains in term of ultimate capacity of RC deep beam with openings strengthened with CFRP wraps.

CHAPTER 2

LITERATURE REVIEW

2.1 INTRODUCTION

A number of good deal of studies has been carried out on deep beam with openings in the last few decades. The previous research results deals with the experimental study of the behaviour of RC deep beams contained with large opening will be focused on this chapter.

2.2 OPENING CLASSIFICATIONS

The opening shape, size and location can be varied according to the design.

2.2.1 Shape

Prentzas (1968) considered rectangular, circular, trapezoidal, triangular, diamond and even irregular shapes in his extensive experimental study. Even though there is numerous shapes of transverse opening are available, but rectangular and circular opening shape are the most common one in practice. The circular opening generally uses to facilitate the service pipes such as the electrical supply and plumbing while the air-conditioning ducts are normally made in rectangular shape so they can pass through the rectangular openings of the beam.

2.2.2 Size

In 1974, Somes and Corley considered circular opening is large when its diameter larger 0.25 times than the beam web depth. Later in 1979, Mansur and Hasnat defined the square, circular or nearly square opening in shape as small opening or, in other words, less than the overall depth of beam about approximately 40%. According to Mansur and Tan (1999) have considered the essence to classify the opening either as large or small which lay in the structural reaction of the beam. An opening can be classified as a small opening if the normal beam theory is applicable or, in other words, the opening is small enough to allow the structure to behave like normal beam does. While an opening is considered as large when the normal beam-type behaviours are no longer applied due to the presence of the openings. As reported by Mansur and Tan (1999), the opening depth should not exceed than 50% of the overall depth of the beam. Many researchers have been dealing with the opening size, whether it is small or large opening, but currently there is without any clear-cut demarcation line or definition.

2.2.3 Location

The openings can be located at anywhere in the beam web either in horizontal or vertical directions in the region between the support and point load applied. It also can be within high moment or low shear zone. A web opening located in a high moment region has an influence on the loading capacity of the beam, due to the beam stiffness is weak in that area, and collapse load defined by this opening (Torunbalci, 2000, 2002). In 1969, Hanson tested a series of longitudinally RC T-beams with square and circular opening in the web and found that the inclusion of opening located adjacent to the centre stub (support) lead to zero strength reduction. The behaviour of 8 reinforced concrete continuous beams with large web openings was investigated by Mansur *et al.* (1991). They were discovered that the location of the opening has very insignificant effect in the term of cracking load, but placed the openings in a comparatively high moment region generate a large deflection and smaller collapse load. The collapse mode remains unaffected by the location of opening virtually.

In contrast, the researches of Kong and Sharp (1977) and Ashour and Rishi (2000) revealed that the strength of beam, stiffness and failure mode are primarily dependant upon the location and size of the opening. They disclosed the strength of the beam was reduced when the location of opening interrupted the natural load path of the beam. Other than that, the inclusion of opening in the interior shear span resulted the highest load capacity reduction occurred. The ultimate shear capacity and beam strength was cut down when the opening interrupted the natural load path of the beam or the stress field joining the loading and the reaction point were intercepted by the opening. (Ashour and Rishi, 2000; Campione & Minafò, 2012). In addition, Mansur and Tan (1999) also contributed the guidelines to select the location of web openings. They concluded the location of openings should not be placed closer than half of the beam's depth to the supports in order to prevent the crucial zone for the congestion of reinforcement and shear failure happen. In a similar way, an opening location should not nearer than 0.5D to any concentrated loads.

The spacing of the opening from the top and bottom of the beam also affects the load-carrying capacity of a beam. The eccentricity of the web openings is closest to the applied load is increased downward below the longitudinal beam axis. The domination of the tensile stressed in the region below the opening, and these stresses are compensated by the existing tension reinforcement. In the meantime, the axial compressive stress is compensated by the concrete at the part above the opening. When the opening is close to the support, the situation is reversed. When openings are above the longitudinal axis of the beam, better results are obtained. Hence the load carrying capacity of the beam depends on how much the openings interrupt the compression strut spanning from the support. As a result, opening should be placed below the axis of the beam in the middle of the span and above the axis near the support (Torunbalci, 2000). Javad and Morteza (2004) also concluded the first place to consider the location of the opening in reinforced concrete beam was the middle of the shear span. In order to achieve the ultimate strength of such beams, the opening location should locate near the support.

2.3 METHOD OF STRENGTHENING

There are 2 methods to strengthen the RC deep beams with opening which including internal strengthening and external strengthening. Internal strengthening used the different patterns and quantities of steel bar erected around the opening while external strengthening material by pasting the externally bonded composite materials around the opening in varying arrangement and configuration schemes.

2.3.1 Internal Strengthening Method

This method is favourable when the opening is pre-planned before the construction or during the design stage. The location and size of opening are known in advanced. The web reinforcement played an effective role in controlling the propagation of crack width, upgrading the ultimate shear strength, and deflection that due to stress concentration around the openings. The existence of longitudinal bars on the upper and lower of the opening are very effective in controlling the flexural strains and cracks around the opening. In order to increase the ultimate strength and decrease the deflection of the deep beams with opening, diagonal bars were installed for corner reinforcement as well as the small stirrups at the openings top and bottom (Javad and Morteze, 2004; Ahmed et al., 2012; Kong and Sharp, 1977). In 1990, Siao and Yap concluded that the beams failed by the sudden formation of a diagonal crack in the compression chord due to no additional reinforcement is erected in the members near the opening.

It's also shown that it is necessary to increase the amount of the internal web reinforcement around the opening in order to increase the shear capacity and ductility of RC beams with web openings (Yang *et al.*, 2006; Yang *et al.*, 2007; Yang and Ashour 2008). In additional, inclined web reinforcement is the most effective arrangement in resisting cracks of diagonal in solid deep beams as well as upgrading the ultimate shear strength of solid deep beams. Therefore, the beneficial effect of inclined web reinforcement is even more prominent in the deep beams with openings. (Tan *et al.*, 2004)

2.3.2 External Strengthening Method

In contrast, the second method is much beneficial when the opening is introduced after the construction which cannot meet any design consideration and analysis about the opening. The openings were drilled in an existing structure while the problem may arise during and after the process. This happened often due to the M&E engineers re-locate the opening location to simplify the arrangements of ducts and pipes in order to achieve the huge savings in term of costs, materials and time. Hence, strengthening by using externally bonded FRP system is very crucial. (Alsaeq, 2014; Chin *et al.*, 2011).

2.4 EXTERNALLY BONDED COMPOSITE MATERIALS

Fiber Reinforced Polymer also known as Fiber Reinforced Plastic which is well known to strengthen, repair, upgrade and retrofit the reinforced concrete structural members in the construction industry around the worldwide. FRP composites provide excellent properties which are not available in the conventional construction materials such as good fatigue properties, non-corrosive characteristics, high strength-to-weight ratio, electromagnetic resistance and versatility dealing with different corners and sectional shapes. The ease of handling FRP wrap gives an advantages over the traditional strengthening techniques. (Abdalla *et al.*, 2003; Ban & Abduljalil, 2014). There are several kinds of FRP in the construction industry, most common type of FRP in practice is made by glass, aramid, or carbon fiber that generally in the form of strips, wraps, laminates and sheets. The amount and configuration of FRP laminates strongly influenced the increase in ductility and strength of reinforced concrete structures.

2.4.1 Amount

One of the factors to re-gain the shear strength relies on the number of the FRP layers. Increase the amount of the FRP sheets from one to two layers did increased the shear capacity, but the additional shear capacity gain was not proportional to the additional amount of the CFRP if debonding of CFRP controls the failure (Triantafillou and Antonopoulos, 2000; Chaallal *et al.* 2002). Bousselham and Chaallal (2006b) also revealed that increasing in the amount of the CFRP in deep beams had no noticeable result on the gain in the shear capacity in their experimental studied.

2.4.2 Orientation and Configuration Schemes

The configurations of strengthening system had a great impact on the beam strength and stiffness. It is very important for the CFRP wraps to intercept the potential shear crack, thus can provided effectively to the shear strength of the beam. Pimanmas (2010) found that placed the FRP rods around the opening simply was not much effective due to diagonal crack propagated through the beam with crack paths were migrated to avert make friends with the FRP rod. There are two methods to improve by the FRP rod, which are enclosing the opening and pasting it throughout the whole entire beam depth diagonally. The author also found that the use of inclined near-surface-mounted composite rods externally installed diagonally to the beam axis alongside the opening throughout the entire beam depth can fully recover the shear capacity of RC beams with web opening. When the FRP rods were applied throughout the entire beam depth, an impressive improvement in ductility and loading capacity was observed, which is quite similar with strengthening by internal steel reinforcement. Thus the mode of failure was recovered.

Other than that, Allam (2005) was conducted an experimental studied regarding the efficiency of strengthening beams externally with large shear opening. They employed both CFRP sheets and steel plates to strengthen the beams with opening as well as their configuration schemes. His experimental results showed that the efficiency of CFRP in strengthening the beams with opening when it was applied to both inside and outside opening edges. The improvement of strengthening the outside edges only was also discovered to be more remarkable. Moreover, the application of steel plates to strengthen the beam provided with opening was much more prompt than a case of CFRP sheets.

It was also found that orientated the fibers in perpendicular direction to the potential diagonal shear cracks more effective than others. Ashour and Rishi (2000) concluded that the vertical FRP reinforcement was enhanced the strength than placed it in horizontal. The Vertical FRP shear strengthening lead to an improvement of shear strength about 79% at 1.875 shear span-to-depth ratio, whereas only re-gained 46% shear strength at 1.25 shear span-to-depth ratio. The result showed the performances of the FRP system declined as the behaviour of a shallow beam changes to a deep beam.

2.5 Review of Previous Experimental Studies

Plenty of studies have been carried out by researchers on RC beams with openings to examine the load deflection response, cracking and ultimate behaviour of such beams in the last 4 decades. The major variables investigated included the location, shape and size of the opening, shear span-to-depth ratio, the presence and amount of steel reinforcement around the opening as well as the concrete compressive strength.

2.5.1 Behaviour of RC Deep Beams with Openings

Kong and Sharp (1977) found three types of failures in their extensive test. A total of 72 simply supported deep beams were tested, which included 16 normal weight concrete beams and 56 lightweight concrete beams. The test variable were the sizes and location openings along with different web reinforcement arrangements. Failure mode 1 indicated the same mode of failure that generally present in solid deep beam where when opening did not interfere the natural load path of the beam. Modes of failure 2 and 3 presented when the natural load path of the beam was intersected. A diagonal crack occurred from the inside edge of the support and propagated to the farther bottom corner of the opening for these failure modes. On the top of the opening, diagonal crack occurred between the top corner of the opening and outside edge of the load point.